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14. ABSTRACT

This report describes a research effort to develop a systematic feedback design methodology for complex dynamical systems. Particular attention is given to the problem of shaping the response of lumped and distributed parameter systems having nonlinear dynamics.

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NONLINEAR CONTROL SYSTEMS

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Submitted by

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CONTENTS

CHAPTER I
EXECUTIVE SUMMARY

The principal goal of this research program is to develop a systematic methodology for the design of feedback control schemes capable of shaping the response of complex dynamical systems. A continuation of an ongoing research effort, the specific research program is aimed at the development of a systematic control methodology for lumped and distributed parameter systems, applicable to both the equilibrium and the nonequilibrium cases. The typical design objectives would involve designing feedback schemes which achieve one or more of the following: asymptotic tracking, (an appropriate form of) internal stabilization, and asymptotic disturbance rejection. In the equilibrium case, when taken together these form the control task classically known as the servomechanism problem, or the problem of output regulation.

More generally, the ability to systematically control, or take advantage of, dominant nonlinear effects in the evolution of complex dynamical systems, in both the equilibrium and nonequilibrium setting, is an important research goal with applications in several existing and emerging DOD research and development programs. Notable examples of nonlinear phenomenon within the aerospace industry include the development of flight controllers for increasing the high angle-of-attack or high agility capabilities of existing or future generations of manned or unmanned aircraft. Nonlinear effects, such as the couplings between the pitch, roll and yaw moments at high angles-of-attack, are accentuated in such emerging technologies, as well as in the design of super-agile nonlinear missiles which, for example, require high-angle-of-attack maneuvers for rear hemisphere engagements.

Tacit in the goal of shaping the steady-state response of a nonlinear system is the very existence of a steady-state response and, indeed, the assumption that the notion of steady-state response is well-defined. This has involved careful reconsideration of many basic concepts of nonequilibrium nonlinear dynamics, including the notion of the ω-limit set of a set and its consequences for dissipative systems in the sense of modern nonequilibrium nonlinear dynamics. These ideas make it possible to formulate and begin to solve

the problem of output regulation, in a nonequilibrium setting, for both finite and infinite dimensional control systems.

Our objectives for distributed parameter systems included the development of a unified theory of output regulation for linear and nonlinear distributed parameter systems, with control inputs and outputs acting through the boundary of the spatial domain - in which case the input and output operators are unbounded. Typical applications involving unbounded input and output operators arise in mathematical models for control problems for fluid dynamic systems, systems with (e.g., communications) delays in the inputs or outputs, or the control of tubular chemical reactors.

In contrast to the lumped case, however, is an opportunity provided by the infinite dimensional setting is the possibility of incorporating infinite dimensional exogenous systems. For example, the cancellation of acoustic signals would require rejecting a disturbance produced by an infinite dimensional exosystem, such as a wave equation which would generate a signal with an infinite number of harmonics having known (natural) frequencies but unknown amplitudes or phases. As another example, repetitive control typically requires asymptotic tracking of an infinite saw-tooth wave. In this direction, the research team have succeeded in extending the scope of applicability of regulator theory by making it possible to accommodate infinite dimensional exosystems.

Finally, in our previous work on output regulation, the research team developed a novel method for developing asymptotic proxies for state feedback laws. Closer investigation led to the serendipitous solution of some unsolved problems in signals and systems which can be couched as interpolation problems in finite dimensional subspaces of H^2. Indeed, inspired by the engineering applications of classical interpolation problems in circuits, systems and signal processing, the research team have generalized this to the case of arbitrary (possibly infinite dimensional) subspaces.

CHAPTER II

RESEARCH TASKS AND ACCOMPLISHMENTS

2.1 Output regulation for lumped nonlinear systems

An essential aspect of output regulation, in both the equilibrium and the nonequilibrium cases, is the development of a model for a system which generates the disturbances to be rejected or the signals to be tracked. The generators of these two types of signals can be connected in parallel, so that in this research it is typically assumed that there is one exogenous signal generator.

One of our objectives was to investigate the properties of exogenous signal generators, as well as to delineate the properties of bounded signals which can be generated by exogenous systems with an appropriate form of stability. The goals of this research thrust were described in Tasks 2.1 - 2.2 in the body of our proposal. In the classical equilibrium approach to output regulation, in order to produce periodic exogenous signals one is forced into the unecessary compromise of using an exosystem with an equilibirium, such as the harmonic oscillator. As an extreme example, in the nonlinear case, every perioidic singal, with a given period, is ome nonlinear output of the one-dimensional system $\dot{\tau} = 1$. Along the lines of Tasks 2.1 - 2.2, classical output regulation theory has been considerably enhanced by including nonlinear exosystems with no equilibria.

Another of our objectives, posed in Task 2.3, was to develop the foundations for a non-equilibrium theory of nonlinear output regulation, giving a more general (non-equilibrium) definition of the problem.

Indeed, in our research on this task, the research team has laid the foundations for a non-equilibrium theory of nonlinear output regulation, giving a more general (non-equilibrium) definition of the problem, deriving necessary conditions, and, using these necessary conditions, to present a set of sufficient conditions and a design methodology for the solution of the problem in question. Our analysis leads to a non-equilibrium enhancement of the internal model principle, which can be expressed as a relationships between two uniformly stable attractors. The first is an attractor for the combined dynamics of the exogenous sig-

nal generator and the so-called zero-dynamics of the plant to be controlled, intrinsic to the formulation of the problem. The second is the uniformly stable attractor for the dynamics of the closed-loop system determined by the controller which solves the problem of output regulation, under hypotheses which are non-equilibrium enhancements of those familiar from the equilibrium case. This enhancement of the internal model principle asserts, roughly speaking, that any controller solving the problem of output regulation has to contain a copy of an attractor which may combine the dynamics of the exogenous system with certain nontrivial steady-state motions occurring in the plant to be controlled. In the simple case in which there is only one (and trivial) such steady-state motions, and the analysis is only local, the theory developed reduces to the one presented in our earlier work. On the other hand, the more general approach discussed here makes it possible to solve problems to which none of the existing design methods for output regulation is applicable.

The foundations of this theory have been presented in [13]. The basic assumptions considered in this work no longer include the assumption, common to all earlier literature, that the zero-dynamics of the controlled plant have a globally asymptotically stable equilibrium. Rather, this assumption is replaced with the (substantially weaker) hypothesis that the zero dynamics of the plant "augmented by the exsosystem" have a compact attractor. In this work, though, the (rather strong) assumption, itself also common to all earlier literature, that the set of all "feedforward inputs capable of securing perfect tracking" is a subset of the set of solutions of a suitable *linear* differential equation (assumption of "immersion" into a linear system) has been retained. In the subsequent paper [14] it is shown that, within the new framework, the assumption of linearity can also be weakened and replaced by the assumption that the set in question is a a subset of the set of solutions of a suitable *nonlinear* differential equation (assumption of "immersion" into a nonlinear system). In [18], the results summarized above have been extended to the case of a system having higher relative degree, by showing how output regulation can be achieved by means of a (dynamic) pure error feedback. Finally, in the work [19] it is shown that an "immersion" assumption is not in principle needed in solving a problem of nonlinear output regulation by output feedback. Under the only assumption that the zero dynamics of the controlled system have

bounded trajectories, it is shown that there exists a controller solving the problem. The design procedure illustrated in the paper is based on some recent results, developed by Andrieu and Praly, on the theory of nonlinear state observers originally proposed by Kazantiz and Kravaris. The internal model obtained in this way is a linear Hurwitz system with nonlinear output map.

Given the unanticipated success in pursuing Task 2.3, it was not necessary to address the issues in Task 2.6, which focused on the development of systematic design methods for output regulation in case some of the reference trajectories are known functions of time.

Task 2.4 represented an important next step in the development of a nonequilibrium theory for output regulation. It proposed the development of systematic methods for the design of feedback laws achieving output regulation for broad classes of exosystems and nonlinear control systems whose zero dynamics have a compact, Lyapunov stable attractor. This has been achieved by F. Celani in his Ph.D. thesis, which has appeared in archival form in [15].

Tasks 2.5 and 2.7 focus on the development of systematic design methods for adaptive or robust output regulation in the nonequilibrium case. The works [16, 17] show how the theory of nonlinear adaptive observers can be effectively used in the design of internal models for nonlinear output regulation. The theory substantially enhances the existing results in the context of adaptive output regulation, by allowing for not necessarily stable zero dynamics of the controlled plant and by weakening the standard assumption of having the steady state control input generated by a linear system.

Finally, contributions to the problem of output regulation on large domains of intitial data remain a substantial challenge to developing a fairly complete nonequilibrium theory of output regulation, especially in the adaptive or robust case. This program has attracted significant attention in the recent literature. The recent Ph. D. thesis by Nathan McGregor, which is announced in [20] and developed further in [21], contains important contributons to this program.

2.2 Moment problems for signals, systems and control

In our work on output regulation, a novel method was obtained for developing asymptotic proxies for state feedback laws in terms of interpolation problems in finite dimensional subspaces of H^2, with a degree constraint. This yields a smooth complete parameterization of all such interpolants and pairs of convex optimization problems for determining any interpolant in this class (see [22] - [24] and the references therein). In particular, the parameterization is in terms of spectral zeros, and for any choice of spectral zeros the interpolant is obtained by minimizing a certain convex entropy functional. Hence the spectral zeros can be used in applications (e.g., robust control and signal processing) for tuning. A case in point is sensitivity shaping in robust control. The questions of what shapes are feasible leads to an interesting inverse problem. More specifically, one can now answer the following two questions. First, given a function f which satisfies specified interpolation conditions, when is it that f can be obtained as the minimizer of a suitably chosen entropy functional? Second, given a function g, when does there exist a suitabe entropy functional so that the unique minimizer f which is subject to interpolation constraints also satisfies $|f| = |g|$ on the unit circle. The theory and answers to these questions suggest an approach to identifying interpolants of a given degree and of a given approximate shape.

The focal point of Task 2. 8 was the development of this tool for multivariable systems. In this [26], the research team has continued previous work by generalizing the theory of analytic interpolation with degree constraints to the matrix case.This led to the further development of some aspects of the a theory of the bi-tangential Nevanlinna-Pick interpolation with complexity constraints, which is a natural extension of our previous theory in the scalar and matrix cases. In analogy with this earlier theory, a complete parameterization is presented in terms of a parameterized pair of convex optimization problems for solving the bi-tangential Nevanlinna-Pick interpolation problem. It is also shown to reach the greatest level of generalization if one insists on keeping the convex optimization structure. The superiority of pure matrix theory, when it comes to tuning, is also demonstrated.

In another direction, these finite dimensional interpolation results have been extended to the infinite dimensional setting [25]. In particular, a synthesis of the differentiable ap-

proach to the generalized moment problem is developed, an approach which begins with a reformulation in terms of differential forms, and a canonically derived, strictly convex optimization problem. Engineering applications typically demand a solution that is the ratio of functions in a certain finite dimensional vector space of functions, usually the same vector space that is prescribed in the generalized moment problem. Solutions of this type are hinted at in the classical text by Krein and Nudelman and stated in the vast generalization of interpolation problems by Sarason. Formulated as generalized moment problems with a complexity constraint, this gives a complete parameterization of such solutions, in harmony with the above mentioned results and engineering applications. While our previous results required some differentiability hypotheses, one now only requires a weak form involving integrability and measurability hypotheses that are more in the spirit of the classical treatment of the generalized moment problem. Because of this generality, one can extend the existence and well-posedness of solutions to this problem to nonnegative, rather than positive, initial data in the complexity constraint. This has nontrivial implications in the engineering applications of the theory. This more general result has been extended to the case where the numerator can be an arbitrary positive absolutely integrable function that determines a unique denominator in this finite-dimensional vector space.

2.3 Nonlinear oscillations

The focus of Tasks 2.9 and 2.10 are the development of criteria for the existence of sustained oscillations for a differential equation defined on Euclidean space and the plan to use such a criterion to determine the behavior of higher dimensional phase-locked loop circuits. In two dimensions, Poincaré-Bendixson Theory gives a complete criterion for the existence of periodic orbits for differential equations leaving a bounded domain invariant and having no equilibria in the domain. In higher dimensions, some initial progress on this program has been made, as reported in [12]. Furthermore developments include a fairly general set of criteria which can be tested infinitesimally.

As an example of the results developed in [12], there is the following generalization of the Poincaré-Bendixson theory.

Definition 2.3.1. *(Pliss) Suppose $M \subset \mathbb{R}^n$ is a bounded domain with smooth boundary. If $\overline{M}$ is diffeomorphic to $\mathbb{D}^{n-1} \times S^1$, then M is a toroidal region.*

An angular one-form on a bounded domain D for a vector field X in $\mathrm{Vect}(\mathbb{R}^{\mathrm{n}})$ is a closed differential $\omega = \sum_{i=1}^{n} a_i dx_i$ such that

$$\langle \omega, X \rangle > 0 = \sum_{i=1}^{n} a_i X_i > 0$$

where X_1, for $i = 1, \ldots, n$ are the components of the vector field X.

Theorem 2.1. *Suppose $X \in \mathrm{Vect}(\mathbb{R}^{\mathrm{n}})$ defines a differential equation $\dot{x} = f(x)$ on $\mathbb{R}^n$ which leaves a toriodal region M positively invariant. If X has an angular one-form, then X has a periodic solution.*

Future research directions include the continuing development of the general criterion underlying this result as well as its applications to specific differential equations, such as those describing a phase-locked loop circuit.

2.4 Output regulation for distributed parameter systems

2.4.1 Zero Dynamics Controller for Linear Parabolic Systems

In a series of papers (see e.g., [5, 6]) a systematic methodology for solving certain problems of output regulation for a class of linear abstract boundary control systems using dynamic and static controllers has been developed. For the special systems considered in this work, the controllers are designed using controllers or static feedback derived from an associated zero dynamics system. The zero dynamics is obtained from the plant by constraining the error (the difference between the measured output and signal to be tracked) to be zero. Under our assumptions the proof of the main result is very simple. Moreover, in applications this result is quite easy to apply and provides a very simple design procedure for a wide range of problems that can otherwise be difficult to solve. Thus far, numerous colocated and non-colocated examples have been studied The method is most readily applicable in colocated case. Indeed, the noncolocated case is somewhat different requiring

a more lengthy development and is currently part of our ongoing research. These methods have also been applied in the case of interior point control in [7].

A unifying methodology for both lumped and distributed parameter systems, there are several advantages of the zero dynamics controller methodology:

1. The algorithm is straightforward. The assumptions are generally easily verified.
2. The design is easily applied to co-located boundary control systems governed by partial differential equations.
3. The method is applicable to linear and nonlinear problems.
4. Low order controllers may be obtained from Steady State Response of the zero dynamics.
5. It easily adapts to handle rejection of known disturbances.
6. The design methodology has been extended to handle several interesting non-colocated and even nonlinear examples.
7. The method also works well for interior point control.

2.4.2 The Geometric Theory for the Regulator Equations

In all of its generality, the origin of the geometric approach to output regulation derives from the earlier work of Francis [8] and Francis and Wonham [11].

In particular, it is still quite common that the reference signal and disturbance are considered (using a parallel sum connection) to be generated by a common finite dimensional exosystem

$$
\begin{aligned}
&\dot{w} = Sw, \;\; w(0) = w_0, \qquad (2.1)\\
&y_r = Qw\\
&P = \mathcal{P}w
\end{aligned}
$$

where $w \in W$ a finite dimensional vector space, $S \in \mathcal{L}(W)$, $\mathcal{P} \in \mathcal{L}(W, Z)$ and $Q \in \mathcal{L}(W, U)$ (here U is the input space).

For a broad class of linear infinite dimensional systems, it is also generally possible to

rewrite the overall system in the more standard systems theoretic form

$$z_t = Az + Bu + \mathcal{P}w,\ z(0) = \varphi, \tag{2.2}$$

$$y(t) = \mathcal{C}z(t), \tag{2.3}$$

$$\dot{w} = Sw,\ \ w(0) = w_0.$$

In the simplest cases, under quite general assumptions, a state feedback law solving the output regulation problem is solvable by a feedback control u in the form

$$u = Kz + (\Gamma - K\Pi)w$$

where K is any stabilizing feedback for the pair (A, B) and $\Pi \in \mathcal{D}(A) \subset \mathcal{L}(\mathcal{W}, \mathcal{Z})$ and $\Gamma \in \mathcal{L}(\mathcal{W}, \mathcal{U})$ are operators satisfying the *Regulator Equations*:

$$\begin{aligned} \Pi S &= A\Pi + (B\Gamma + P) \\ C\Pi - Q &= 0 \end{aligned} . \tag{2.4}$$

Under the additional hypotheses that the operator A in (2.2) generates an exponentially stable semigroup, one may take $K \equiv 0$ and simply seek $u = \Gamma w$.

The geometric approach to the design of control laws solving problems of this type has received considerable attention in the literature. A number of authors ([1], [9], [10]) have extended finite dimensional geometric methods to the infinite dimensional case and characterize solvability of the regulator problem for distributed parameter problems, with bounded input and output operators.

For unbounded B and C this task is much more difficult. 5n [4] some preliminary results have been derived in this case for the class of regular linear systems. A main complication here is showing that a given systems is described by a regular linear linear system. In [6] it is shown that a general class of parabolic boundary control systems satisfies our underlying assumptions for solvability of the regulator equations and the output regulation problem.

2.4.3 Nonlinear Distributed Parameter Systems

As this program goes forward, one of the longer term goals is the development of a theory of nonlinear output regulation as parallel as possible to the theory for linear problems. For linear parabolic problems a complete characterization of those state feedback control laws $u = \Gamma w$, which solve a problem of output regulation for a stable linear system with bounded inputs and outputs, has been developed. Several results for special classes of nonlinear problems are also obtained.

While output regulation is an asymptotic theory and the long time existence of solutions to open-loop nonlinear distributed parameter systems remains extremely challenging, there has been some success in establishing long time existence and asymptotic behavior for the control of certain examples or system classes using particular feedback design methods ([1, 2, 5]). Still, the control of nonlinear distributed parameter systems is sufficiently difficult that the current efforts have primarily focused on local results for output regulation with respect to signals and disturbances generated by finite-dimensional exogeneous systems, where techniques such as center manifold methods can yield some powerful insights.

These local techniques are not simply an appeal to linearization. Even in the lumped nonlinear case, elementary examples show that a solution to the problem of output regulation for the linearization does not solve the output regulation problem for the nonlinear problem.

2.5 Masters Thesis

Marinos Baghdati

`http://etd.lib.ttu.edu/theses/available/etd-04072005-145838/`

A general theory is presented for solutions to problems of output regulation for boundary control of bounded domains in R^2. This theory is then applied to address the special case where the domain in R^2 is a rectangle. The problems considered are ones involving the two dimensional heat equation, where both the controlling and sensing occur on one side of the rectangle, and the solutions are obtained through a zero dynamics controller design. The solution methods presented involve both an analytical approach, as well as a

numerical approach.

Matthew Walker

http://etd.lib.ttu.edu/theses/available/etd-04112005-141405/

A general methodology is described for designing feedback control laws achieving output regulation for a class of linear plants that evolve in an infinite dimensional state space. In addition several examples illustrating the methodology for colocated and non-colocated actuator and sensor pairs are provided. Also considered are some examples of output regulation for a nonlinear plant governed by Burgers' equation. The basic problem is to find a boundary control which forces the output of a distributed parameter system to asymptotically (as time goes to infinity) track a prescribed trajectory. The design methodology is based on the zero-dynamics system, a system formed from the plant by requiring the error to be zero. This thesis will discuss the zero-dynamics system in depth by examining many examples of control problems.

Vijay Moses Johnson

http://etd.lib.ttu.edu/theses/available/etd-08012005-130440/

This research work is concerned with the numerical implementation of a geometric design methodology for obtaining feedback control schemes capable of shaping the response of dynamical systems governed by hyperbolic partial differential equations. This work focuses on asymptotic tracking. This type of problem represents one of the central problems in control theory. In this work numerical approximations of control laws for controlling a plant, described by hyperbolic partial differential equations, are obtained in order to have the output track a reference signal (and/or reject a disturbance) produced by a finite dimensional external generator or exogenous system. Two different kind of examples of set-point and harmonic tracking are dealt with this work, one for One Dimensional Wave Equation and the other for Hinged Beam Equation. Modified Euler Method is used for solving the two equations numerically.

REFERENCES

[1] C.I. Byrnes, D.S. Gilliam, I.G. Laukó and V.I. Shubov, “Output regulation for linear distributed parameter systems,” *IEEE Trans. Aut. Control.*, 45, No.12, 2236-2252 (2000).

[2] C. I. Byrnes, D.S. Gilliam, A. Isidori and V.I. Shubov, “Set point boundary control for a nonlinear distributed parameter system,” *Proceedings of the 42nd IEEE Conference on Decision and Control*, pp 312-317, Dec 9-12, 2003, Maui, Hawaii.

[3] C. I. Byrnes, D.S. Gilliam, A. Isidori, V.I. Shubov, “Static and Dynamic Controllers for Boundary Controlled Distributed Parameter Systems,” *Proceedings of the 43rd Conference on Decision and Control*, Nassau, The Bahamas, December (2004).

[4] C. I. Byrnes, D.S. Gilliam, V.I. Shubov, G. Weiss, “The state feedback regulator problem for regular linear systems,” preprint TTU, 2002.

[5] C. I. Byrnes, D.S. Gilliam, A. Isidori, V.I. Shubov, “Static and Dynamic Controllers for Boundary Controlled Distributed Parameter Systems,” *Proceedings of the 43rd Conference on Decision and Control*, Nassau, The Bahamas, December (2004).

[6] C.I. Byrnes, D.S. Gilliam, A. Isidori, V. Shubov “Zero Dynamics Modeling and Boundary Feedback Design for Parabolic Systems,” *Mathematical and Computer Modelling*, 44 (2006), no. 9-10, (co-authors), pp. 857–869.

[7] C. I. Byrnes, D.S. Gilliam, A. Isidori, “Interior Point Control of a Heat Equation Using Zero Dynamics Design,” *Proceedings of 2006 American Control Conference* 2006.

[8] B. A. Francis, *The linear multivariable regulator problem*, SIAM Journal of Control and Optimization, 14:486–505, 1977.

[9] S. A. Pohjolainen, “On the asymptotic regulation problem for distributed parameter systems,” *Proc. Third Symposium on Control of Distributed Parameter Systems*, Toulouse, France (July 1982).

[10] J.M. Schumacher, “Finite-dimensional regulators for a class of infinite dimensional systems,” *Systems and Control Letters*, 3 (1983), 7-12.

[11] B. A. Francis and W. M. Wonham, *The internal model principle of control theory*, Automatica, 12:457–465, 1976.

[12] C. I. Byrnes, “Differential Forms and Dynamical Systems,” to appear in *The Picci Festschrift*, 2007.

[13] C.I. Byrnes, A. Isidori, “Limit sets, zero dynamics and internal models in the problem of nonlinear output regulation, *IEEE Transactions on Automatic Control*, **AC-48**, pp. 1712-1723, (2003).

[14] C.I. Byrnes, A. Isidori, “Nonlinear internal models for output regulation,” *IEEE Transactions on Automatic Control*, **AC-49**, pp. 2244-2247, (2004).

[15] C.I. Byrnes, F. Celani, A. Isidori, “Omega limit sets of systems that are semiglobally practically stabilized,” *Int. J. of Robust and Nonlinear Control*, **15**, pp. 315-333 (2005).

[16] F. Delli Priscoli, L.Marconi, A. Isidori, “A New Approach to Adaptive Nonlinear Regulation, *SIAM J. Contr. and Optimiz.*, 45 (2006), no. 3, 829–855.

[17] F. Delli Priscoli, L.Marconi, A. Isidori, “Adaptive Observers as Nonlinear Internal Models,” *Systems and Control Letters*, 55 (2006), no. 8, 640–649.

[18] C.I. Byrnes, A. Isidori, L. Marconi, “Further results on output regulation by pure error feedback,” *Proceedings of IEEE CDC 2005*.

[19] C.I. Byrnes, A. Isidori, L. Marconi, L. Praly, Nonlinear Output Regulation Without Immersion, *Proceedings of IEEE CDC 2005*.

[20] N. K. McGregor, C.I. Byrnes, A. Isidori, “Results on Nonlinear Output Regulation for MIMO Systems,” *Proceedings of ACC 2006*.

[21] N. K. McGregor, C.I. Byrnes, A. Isidori, “Global robust output regulation for a class of uncertain nonlinear systems,” to appear in *Systems and Control Letters*.

[22] C. I. Byrnes and A. Lindquist, “Variational problems and global inverse function theorems,” *Intern. Journal of Robust and Nonlinear Control* **16** (2007) 1 -18.

[23] C. I. Byrnes and A. Lindquist, “The generalized moment problem with complexity constraint,” *Integral Equations and Operator Theory*, 56 (2006) 163 -180.

[24] C. I. Byrnes and A. Lindquist, “The uncertain generalized moment problem with complexity constraint,” *New Trends in Nonlinear Dynamics and Control*, W. Kang, M. Xiao and C. Borges (Eds.), Springer Verlag, 2003, 267–278.

[25] C.I. Byrnes, T.T. Georgiou, A. Lindquist and A. Megretski, “Generalized interpolation in H^∞ with a complexity constraint,” *Trans. of the American Math. Society*, **358**(3), pp. 965–987, March 2006.

[26] Y. Kuroiwa and A. Lindquist, *Bi-tangential Nevanlinna-Pick interpolation with a complexity constraint*, *Proc. MTNS 2006*, pp. 2541–2563, Kyoto, Japan.

CHAPTER IV
PERSONNEL INFORMATION

4.1 Personnel

Christopher I. Byrnes	Professor, Washington University, St. Louis
Alberto Isidori	Professor, Washington University, St. Louis
David S. Gilliam	Professor, Texas Tech University
Anders Lindquist	Professor, KTH, Stockholm, Sweden
Victor Subov	Professor, Texas Tech University
Paul Iglesias	Washington University, St. Louis
Nathan McGregor	Washington University, St. Louis

4.2 Honors & Awards

3 IEEE Fellows (Dr.s C.I. Byrnes, A. Isidori, A. Lindquist).

Dr. A. Lindquist presented Invited plenary lecture at the International Congress on the Applications of Mathematics (ICAM), Santiago de Chile, March 13-17, 2006.

Dr. A. Isidori has been appointed President-Elect of the International Federation of Automatic Control (IFAC).

Dr. Christopher I. Byrnes was awarded the W.T. and Idalia Reid Prize for his contributions to linear and nonlinear systems and control at the SIAM Annual Meeting in July 2005.

Dr. A. Isidori has been installed as Edwin H. Murty Professor of Engineering at Washington University, November 2004.

Dr. A. Isidori has been elected Fellow of IFAC, July 2005.

The paper: C. Bonivento, A. Isidori, L. Marconi, A. Paoli, Implicit fault tolerant control: application to induction motors, *Automatica*, 40, pp. 355-371, (2004) was given the triennial *Automatica* award at the IFAC World Congress in Prague, 2005.

At the 42nd IEEE CDC, Maui, Hawaii, in December 2003, C. I. Byrnes, T. Georgiou and A. Lindquist were awarded the 2003 IEEE George S. Axelby Award for the best paper in the IEEE Trans. on Aut. Control.

The paper *A convex optimization approach to the rational covariance extension problem*, by C. I. Byrnes, S. V. Gusev and A. Lindquist was selected in 2000 to be published in an enhanced form in SIAM Review as a "SIGEST" paper.

At the 40th IEEE CDC, Orlando, Florida, in December 2001, A.Isidori was awarded the 2001 Hendrik W. Bode Lecture prize from the Control Systems Society of IEEE.

Te triennial IFAC Best Paper Award, (C.I. Byrnes and A. Isidori), 1993 IFAC World Congress.

IEEE George S. Axelby Award as the best paper in the IEEE Trans. on Aut. Control, 1991 (C.I. Byrnes and A. Isidori).

Dr. C.I. Byrnes was elected in March 2001 as a Foreign Member of the Royal Swedish Academy of Engineering Sciences.

Dr. C.I. Byrnes, was installed as the Edward G. and Florence H. Skinner Professor of Systems and Engineering at Washington University, St. Louis, 1998.

Dr. C.I. Byrnes, elected Fellow of the Academy of Sciences of St. Louis in 1998.

Dr. C.I. Byrnes was awarded an Honorary Doctorate of Technology from the Swedish Royal Institute of Technology, November 1998.

The Graduate College Distinguished Research Award: C.I. Byrnes, 1988, ASU.

Fellow, Japanese Society for the Promotion of Science: C.I. Byrnes, 1986.

"Quazza Medal" awarded to Dr. A. Isidori at 13th IFAC World Congress in San Francisco, 1996 for "Pioneering and Fundamental Contributions to the Design of Nonlinear Feedback Systems."

Alberto Isidori was listed in the Highly-Cited database among the top 10 most-cited authors in Engineering in the world for the period 1981-1999.

Dr. A. Lindquist, Zaborszky Lecturer for the year 2000.

Dr. A. Lindquist, Gordon McKay Visiting Profesor, Berkeley, 2002.

Dr. A. Lindquist, Israel Pollak Distingushed Lecturer, 2005

Dr. A. Lindquist, Foreign Member of Russian Academy of Natural Sciences, 1997.

Dr. A. Lindquist elected Member of the Royal Swedish Acad. of Engr. Sci., 1996.

Dr. A. Lindquist, Honorary Member of Hungarian Operational Res. Soc., 1994.

CHAPTER V

TRANSITIONS AND DISCOVERIES

5.1 AFRL Point of Contact

Dr. Siva S. Banda, Senior Scientist for Control Theory, Air Vehicles Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. Phone: (937)255-8677, Fax: (937)656-4000, siva.banda@wpafb.af.mil

5.2 Transitions

Dr. Kevin A. Wise, The development of improved(lower cost, lower weight) actuators for UCAV's. This transition by Boeing has been tested using their X-45A simulator, with success.

Elizaberh R. Holohan, lizh@intven.com Intellectual Ventures, Bellevue WA 98004. Speaker recognition for use as a biometric for security systems, and applications to high resolution signal analysis within a desired frequency range. The company (IV) has been in ”due diligence” negotiations, on a monthly basis, with Wash. U. since July, 2005.

Dr. Yutaka Ikeda (Phantom Works Boeing) The internal model principle for harmonic disturbance rejection and for dead zone modeling. This transition began with the application of output regulation, jointly with Dr. Ikeda, to the problem of suppression of harmonic disturbances in a (sanitized) model for take-off and landing of a UAV.

Drs. Gilliam and Shubov have continued their collaboration with Dr. John Burns, at the AFOSR Center for Optimal Design and Control at VPI, on the design of special sensors that damp high frequency oscillations. Applications include problems in regulation (such as active noise suppression) and various topics in hydrodynamics including applications to large eddy simulations (les).

5.3 New Discoveries

C.I. Byrnes and A. Lindquist, *Method and Apparatus for Speech Analysis and Synthesis*, United States Patent 5,940,791, August 17, 1999.

C.I. Byrnes and A. Lindquist, *Method and Apparatus for Speaker Recognition*, U.S. Patent 6,256,609, July 3, 2001.

C.I. Byrnes, A. Lindquist and T.T. Georgiou, *A Tunable High-Resolution Spectral Estimator*, U.S. Patent 6,400,310, June 4, 2002.

One U. S. and 12 extensions or foreign patent applications pending.

CHAPTER VI

PUBLICATIONS

1. A. Blomqvist, A. Lindquist and R. Nagamune, “Matrix-valued Nevanlinna-Pick interpolation with complexity constraint: An optimization approach,” *IEEE Transactions on Automatic Control*, 48 (Dec. 2003), 2172–2190.

2. C. I. Byrnes, “Differential Forms and Dynamical Systems,” to appear in *The Picci Festschrift*, 2007.

3. C. Bonivento, A. Isidori, L. Marconi, A. Paoli, “Implicit fault tolerant control: application to induction motors,” *Automatica*, 40, pp. 355-371, (2004).

4. C.I. Byrnes, F. Celani, A. Isidori, “Omega limit sets of systems that are semiglobally practically stabilized,” *Int. J. of Robust and Nonlinear Control*, **15**, pp. 315-333 (2005).

5. C. I. Byrnes, J. Dockery, D. S. Gilliam, “Bifurcations and Attractors for a Controlled Burgers Equation,” *Proceedings of MTNS 2006*, pp. 1368–1378, Kyoto, Japan.

6. C. I. Byrnes, G. Fanizza and A. Lindquist, “A homotopy continuation solution of the covariance extension equation,” *New Directions and Applications in Control Theory*, W. P. Dayawansa, A. Lindquist and Y. Zhou (eds.), Springer Verlag, 2005, 27–42.

7. C.I. Byrnes, T.T. Georgiou, A. Lindquist and A. Megretski, “Generalized interpolation in H^∞ with a complexity constraint,” *Trans. of the American Math. Society*, **358**(3), pp. 965–987, March 2006.

8. C. I. Byrnes, D.S. Gilliam “The steady-state response of a nonlinear control system, Lyapunov stable attractors and forced oscillations,” to appear in *The Isidori Festschrift*, 2007.

9. C.I. Byrnes, D.S. Gilliam, C. Hu, “Set-point boundary control for a Kuramoto-Sivashinsky equation,” *Proceedings of the 45th IEEE Conference on Decision & Control*, pp. 75-81, San Diego, CA.

10. C.I. Byrnes, D.S. Gilliam, A. Isidori, “Interior Point Control of a Heat Equation Using Zero Dynamics Design,” *Proceedings of the 2006 American Control Conference*, 2006, pp. 1138-1143.

11. C. I. Byrnes, D.S. Gilliam, A. Isidori, J. Ramsey, “On the steady-state behavior of forced nonlinear systems,” New trends in nonlinear dynamics and control, and their applications, 119–143, *Lecture Notes in Control and Inform. Sci.*, 295, Springer, Berlin, 2003.

12. C.I. Byrnes, D.S. Gilliam, A. Isidori, V. Shubov, “Zero Dynamics Modeling and Boundary Feedback Design for Parabolic Systems,” *Mathematical and Computer Modelling*, 44 (2006), no. 9-10, pp. 857–869.

13. C. I. Byrnes, D. Gilliam A. Isidori and V.I. Shubov, “Set-point boundary control for a viscous Burgers equation,” *New Directions in Control Theory and Applications*, Springer Verlag, 2005.

14. C.I. Byrnes, D.S. Gilliam, A. Isidori, V.I.Shubov, “Static and Dynamic Controllers for Boundary Controlled Distributed Parameter Systems,” *Proc. 43rd IEEE Conference on Decision and Control*, pp. 3324-3325, (2004).

15. C. I. Byrnes, D. Gilliam A. Isidori and V.I. Shubov, “Set Point Boundary Control for a Nonlinear Distributed Parameter System,” *Proceedings of the 42nd IEEE Conference on Decision and Control*, pp 312-317, Dec 9-12, 2003, Maui, Hawaii.

16. Byrnes, C. I.; Gilliam, D. S.; Shubov, V. I. “Geometric theory of output regulation for linear distributed parameter systems,” Research directions in distributed parameter systems (Raleigh, NC, 2000), 139–167, *Frontiers Appl. Math.*, 27, SIAM, Philadelphia, PA, 2003.

17. C.I. Byrnes, A. Isidori, “Exploring the Notion of Steady-State Response of a Nonlinear System: Ideas, Tools and Applications,” submitted to Automatica

18. C.I. Byrnes, A. Isidori, “Nonlinear internal models for output regulation,” *IEEE Trans. on Automatic Control*, AC-49, pp. 2244-2247, (2004).

19. C.I. Byrnes, A. Isidori, “Design of nonlinear internal models for output regulation,” *Proc. NOLCOS 2004*.

20. C.I. Byrnes, A. Isidori, “Limit sets, zero dynamics, and internal models in the problem of nonlinear output regulation,” New directions on nonlinear control. *IEEE Trans. Automat. Control* 48 (2003), no. 10, 1712–1723.

21. C.I. Byrnes, A. Isidori, L. Marconi, “Further results on output regulation by pure error feedback,” *Proc. CDC 2005*.

22. C.I. Byrnes, A. Isidori, L. Marconi, L. Praly, “Nonlinear Output Regulation Without Immersion,” *Proc. CDC 2005*.

23. C. I. Byrnes and A. Lindquist, “Variational problems and global inverse function theorems,” *Intern. Journal of Robust and Nonlinear Control* **16** (2007) 1 -18.

24. C. I. Byrnes and A. Lindquist, “A note on the Jacobi Conjecture,” to appear in*Proc. of Amer. Math. Soc.*, 2006.

25. C. I. Byrnes and A. Lindquist, “The generalized moment problem with complexity constraint,” *Integral Equations and Operator Theory*, 56 (2006) 163 -180.

26. C. I. Byrnes and A. Lindquist, “The Covariance Extension Equation Revisited”, *Proc. 2005 CDC*.

27. C. I. Byrnes and A. Lindquist, “The uncertain generalized moment problem with complexity constraint,” *New Trends in Nonlinear Dynamics and Control*, W. Kang, M. Xiao and C. Borges (Eds.), Springer Verlag, 2003, 267–278.

28. C. De Persis, A. Isidori, “Global stabilizability by state feedback implies semiglobal stabilizability by encoded state feedback,” to appear in *Systems and Control Letters*.

29. C. De Persis, A. Isidori, “Global stabilization of nonlinear systems by encoded state feedback,” *Proc. NOLCOS 2004*.

30. F. Delli Priscoli, A. Isidori, “Control engineering approach to congestion control and scheduling in wireless local area network,” *Contr. Engng. Practice*, **13**, pp. 541-558, (2005).

31. F. Delli Priscoli, L.Marconi, A. Isidori, “A New Approach to Adaptive Nonlinear Regulation, *SIAM J. Contr. and Optimiz.*, 45 (2006), no. 3, 829–855.

32. F. Delli Priscoli, L.Marconi, A. Isidori, “Adaptive Observers as Nonlinear Internal Models,” *Systems and Control Letters*, 55 (2006), no. 8, 640–649.

33. G. Fanizza, J. Karlsson, A. Lindquist and R. Nagamune, “Interpretation of passivity preserving model reduction by krylov projection in the context of analytic interpolation with degree constraint,” submitted to Linear Algebra and Applications.

34. T. T. Georgiou and A. Lindquist, “Remarks on control design with degree constraint,” *IEEE Transactions on Automatic Control* **AC-51** (June 2006).

35. T. T. Georgiou and A. Lindquist, “Kullback-Leibler approximation of spectral density functions,” *IEEE Transactions on Information Theory*, 49 (Nov. 2003), 2910–2917.

36. A. Isidori, L. Marconi, “An internal model-based approach to certain pursuit-evasion problems,” *Proc. NOLCOS 2004*.

37. A. Isidori, L. Marconi, “A note on the design of the robust regulator for non-minimum phase linear systems,” *Proc. CDC 2004*.

38. A. Isidori, L. Marconi, C. De Persis, “Observers as Internal Models for Remote Tracking via Encoded Information,” in *Control and Observers Design for Nonlinear Finite and Infinite Dimensional Systems*, T. Meurer, K. Graichen, E.D. Gilles eds., Springer Verlag, LNCIS 322, pp. 3–18.

39. A. Isidori, L. Marconi, C. De Persis, “Remote tracking via encoded information for nonlinear systems,” *Systems and Control Letters*, 55 (2006), no. 10, 809–818..

40. J. Karlsson and A. Lindquist, “On degree-constrained analytic interpolation with interpolation points close to the boundary,” *Proc. MTNS 2006*, pp. 2564–2569, Kyoto, Japan.

41. J. Karlsson, T. Georgiou and A. Lindquist, *The inverse problem of analytic interpolation with degree constraint*, submitted for publication.

42. Y. Kuroiwa and A. Lindquist, *Bi-tangential Nevanlinna-Pick interpolation with a complexity constraint*, *Proc. MTNS 2006*, pp. 2541–2563, Kyoto, Japan.

43. L. Marconi, A. Isidori, “A Note on the Design of the Robust Regulator for Non-Minimum Phase Linear Systems (I),” *Proc. 43rd IEEE Conference on Decision and Control*, pp. 4554-4559.

44. L. Marconi, A. Isidori, A. Serrani, “Non-resonance conditions for uniform observability in the problem of nonlinear output regulation,” *Systems Control Lett.*, 53 (2004), no. 3-4, 281–298.

45. N. K. McGregor, C.I. Byrnes, A. Isidori, “Global robust output regulation for a class of uncertain nonlinear systems,” to appear in *Systems and Control Letters*.

46. N. K. McGregor, C.I. Byrnes, A. Isidori, “Results on Nonlinear Output Regulation for MIMO Systems,” *Proc. ACC 2006*.